

**Climate Extremes and Crop Adaptation
Summary Statement from a Meeting at the Program on Food Security and Environment, Stanford, CA
Held on June 16-18, 2009**



Participants:

David Lobell*, Stanford University
Roz Naylor, Stanford University
Walter Falcon, Stanford University
Marshall Burke, Stanford University
Marc Albertsen, Pioneer
Marianne Banziger, CIMMYT
David Battisti, University of Washington
Jill Deikman, Monsanto
Chris Field, Carnegie Institution
Cary Fowler, Global Crop Diversity Trust
Gurdev Khush, UC Davis
Justin McGrath, Stanford University
Ivan Ortiz-Monasterio, CIMMYT
Matthew Reynolds, CIMMYT
Cristina Rumbaitis Del-Rio, Rockefeller Foundation
Wolfram Schlenker, Columbia University
Claudia Tebaldi, Climate Central

Funder:

The Kendall Foundation

* Responsible for meeting organization and primary drafting of this document.

Introduction

Greenhouse gas emissions from human activity have continued relatively unabated over the past decade, despite the strong intentions and efforts of many around the world. And even as international agreements on climate mitigation appear more likely in the next few years, inertia in the climate and energy systems virtually guarantees a significant amount of climate change over the coming decades. There is therefore great need to adapt climate-sensitive sectors of the economy, and in particular agriculture, to ongoing changes in the climate system. Moreover, a widespread consensus has emerged that, in agriculture, development of new crop varieties will be critical for successful adaptation. However, the ease with which this will occur, or more specifically the additional investments needed to make it happen, has not been thoroughly evaluated.

In June 2009, a group of experts in climate science, crop modeling, and crop development gathered at Stanford University to discuss the major needs for successful crop adaptation to climate change. To focus discussion over the three day period, the meeting centered on just three major crops – rice, wheat, and maize – given that these provide the bulk of calories to most populations. The meeting also focused on two aspects of climate– extreme high temperatures and extreme low moisture conditions (i.e. drought) – that present substantial challenges to crops in current climate and are likely to become more prevalent through time. Other aspects of climate change such as more frequent flooding or saltwater intrusion associated with rising sea levels were not addressed, although they may also be important.

The interdisciplinary nature of the meeting dictated that roughly half of the time was devoted to presentations by some participants to update others on recent progress in their fields. For climate scientists, the task was to explain what is known about the pace of change for different relevant climate variables in different regions. Similarly, crop modelers explained the current understanding of how crops respond to climate variations, and crop breeders explained the recent and potential pace of progress in developing heat and drought tolerant varieties. All participants gained new insights from these prepared materials and the ensuing discussions that entailed the rest of the program.

The current document is split into two sections: a) a brief summary of material presented at the meeting on the current state of climate projections, crop modeling, crop genetic resources and breeding; and b) the collective views of participants on major needs for future research and investment, which emerged from discussions over the three day meeting. The main target audiences for the document are donor institutions seeking to invest in climate adaptation, and climate and crop scientists seeking to set research agendas. We intend the term donor institutions to include private foundations, governments, and inter-governmental organizations such as the World Bank and United Nations. An underlying assumption of the Stanford meeting was that there is a real and growing need to identify specific investment opportunities that will improve food security in the face of climate change. This is reflected, for instance, by the recent G8 announcement of a \$20B investment in food security, the expectation of additional resources for adaptation from the Copenhagen Conference in 2009, and the emphasis of the Obama administration on food and climate issues.

What do we know?

Changes in climate extremes

The most ubiquitous feature of climate change has been – and will continue to be – higher average temperatures in all major cropping regions. This shift in average temperatures alone will cause relevant temperature thresholds for crops, such as 35 °C or 40 °C, to be exceeded on more days in most regions. Materials presented at the meeting showed that climate model projections indicate that these values currently viewed as extreme will be much more common in the future. For example, nearly all models agree that many major cropping regions will experience a rapid increase in days above 35 °C, with most models projecting a more than doubling of the rate of exposure by mid-century (Figure 1).

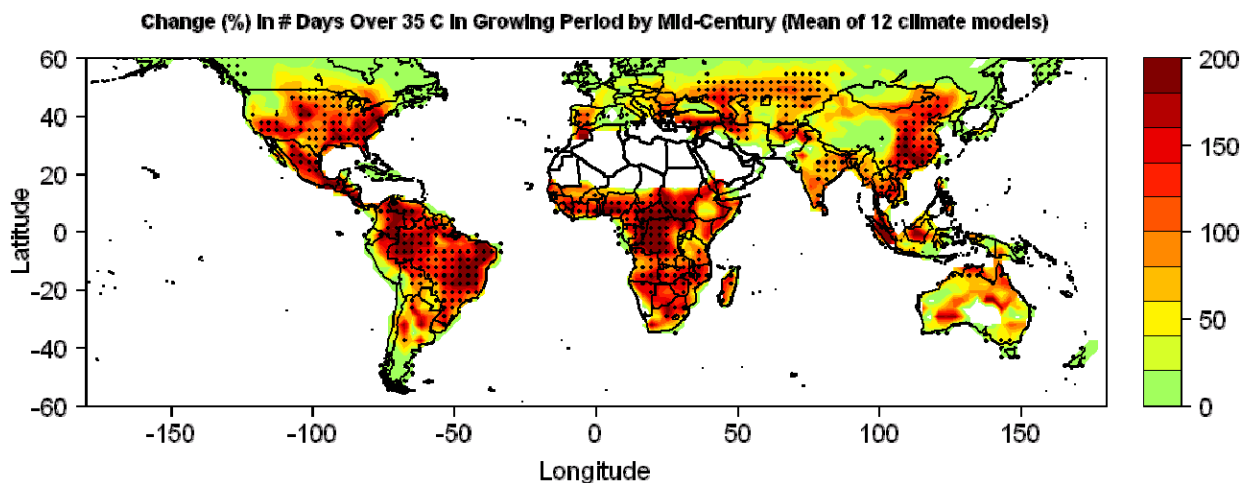


Figure 1. Simulated change in days above 35 C during the growing season in 2050 (% increase above 1990 levels), averaged across 12 climate models. Dots indicate where at least 10 of 12 models agree on the direction of change

Higher average temperatures will also lead to higher evapotranspiration (ET) rates as the water holding capacity of air rises nonlinearly with temperature. Greater rates of ET will, in turn, tend to dry out the soil leading to more frequent occurrence of low moisture extremes. A commonly used indicator of low soil moisture is when the ratio of precipitation over 10 days to ET over the same time period falls below 0.5, and material presented at the meeting showed that this threshold will be more commonly reached in many tropical systems, even accounting for potential changes in rainfall. As a result, the length of the growing period – defined as the longest continuous period of year when the ratio is above 0.5 – is anticipated to shorten in many regions, particularly Southern Africa (Figure 2), and the frequency of plants experiencing low moisture stress is expected to increase.

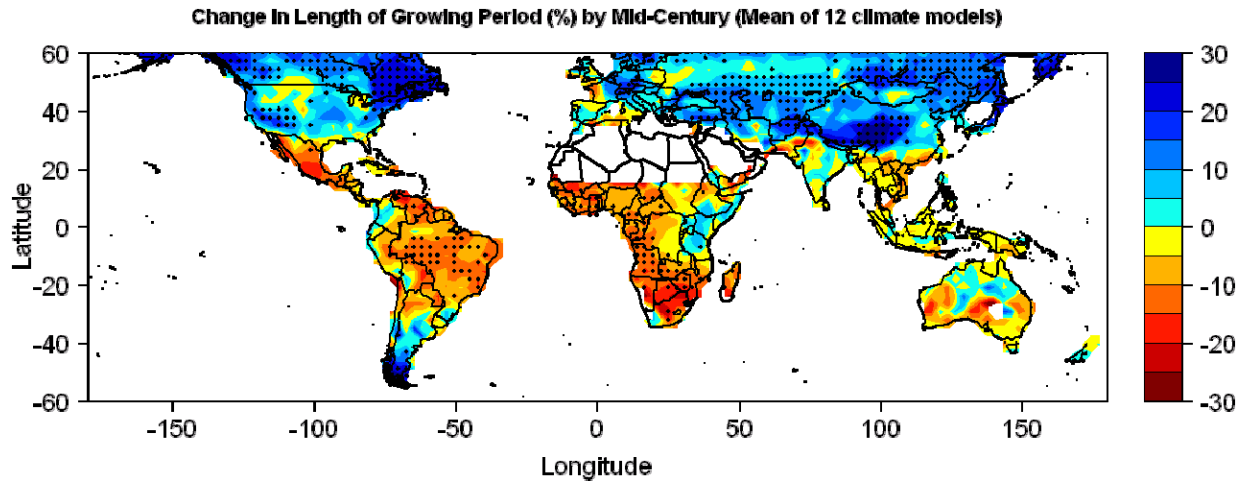


Figure 2. Simulated change in growing season length in 2050 relative to 1990, averaged across 12 climate models. Dots indicate where at least 10 of 12 models agree on the direction of change

In addition to changes in average temperature, extremes could become more common if the year-to-year variability of climate were to increase. Materials presented at the meeting showed that most climate models do a poor job of reproducing current climate variability for summer temperatures, and therefore are not very reliable for examining changes in variability. The level of variability among models varied over a wide range and appeared strongly related to soil moisture levels. Moreover, there is little agreement among models as to whether variability will increase or decrease. It was therefore proposed that more work is needed in this area. Similarly, only one climate model out of 20 appears to do a reasonable job of representing variability due to the El Niño Southern Oscillation, which is a critical driver of rainfall in several regions.

One feature of particular interest to breeders was the likelihood of rapid changes in temperature, either between day and night, or from one week to the next. There is little consensus among climate models on the direction of change in these variables, in large part because they are so dependent on model treatment of clouds and soil moisture. Another important variable is relative humidity, because this will determine the capacity of a canopy to cool itself via transpiration. Humidity is also important for predicting the occurrence and severity of many diseases. Most climate models indicate very small changes in relative humidity, with specific humidity rising at the same rate as the saturation point.

Crop responses to climate extremes

What will the increased occurrence of extremely high temperatures and low soil moisture mean for crop yields around the world? Previous work has shown that most crops in most regions exhibit yield declines with higher average temperatures, with a roughly 10% yield loss per °C of warming a useful rule of thumb. However, nearly all empirical and modeling work has been unable to clearly disentangle whether yield losses are primarily due to the average increase in temperature, or if the extreme days are

disproportionately damaging. Separating the impact of extreme temperatures relative to averages is difficult because of high correlations between the two in most regions – years (or sites) with several hot days tend to be years (or sites) with high average temperatures. However, material presented at the meeting was able to separate the two for maize in the United States by using an unusually large dataset of yields and weather variations to estimate the effect of exposure at each incremental °C. Results suggest a marked drop-off of yields when canopies are exposed to temperatures above 30 °C (see Figure 3). Interestingly, this sensitivity to high temperatures appeared the same for the Southern and Northern half of the Corn Belt, suggesting that varieties grown in the South have not been adapted to decrease sensitivity to extreme heat.

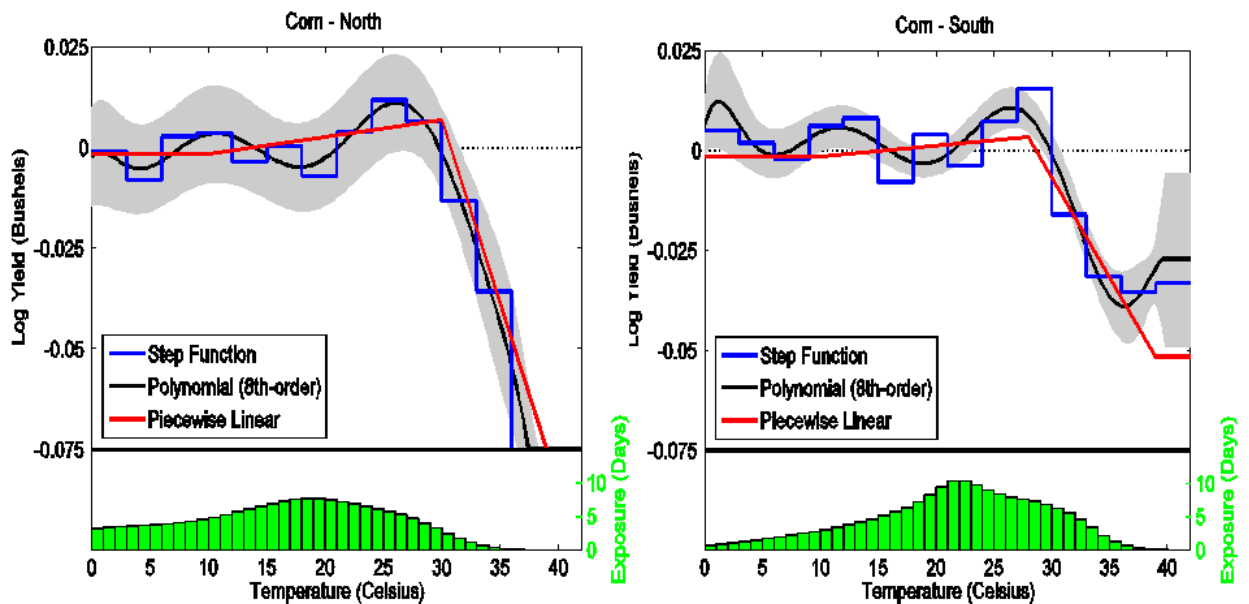


Figure 3. Inferred yield effects of exposure to different temperatures, using three different statistical models. Bottom panels show cumulative time exposed to each degree for counties in analysis. Left shows results for Northern half of Corn Belt in US, right for Southern. (After Schlenker and Roberts, forthcoming in *PNAS*).

A similar approach was then applied to data for maize and other crops in Sub-Saharan Africa. In that case, the data were not sufficient to identify a clear effect of extreme temperatures independent of average temperature effects. However, the data very clearly showed negative yield responses to temperature increases, with expected yield losses of 24% by 2050 for maize in the absence of adaptation (Figure 4).

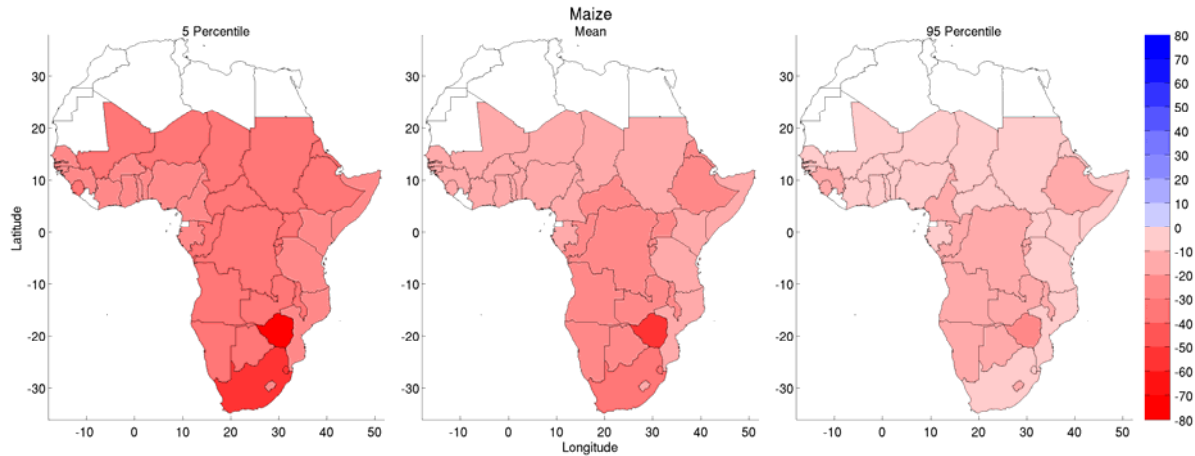


Figure 4. Estimated impacts of climate change by 2050 on maize yields in Africa (% loss relative to 1990), assuming current varieties. Middle panel shows mean projection, while left and right show 5th and 95th percentiles (using pessimistic and optimistic assumptions), respectively. From Schlenker and Lobell (forthcoming in *Environmental Research Letters*).

Results from crop simulation modeling for maize in the United States and Mexico were also presented as a way of exploring the reasons behind the nonlinear response of yields to temperature. Simulated yield losses by CERES-Maize agreed well with estimates from the empirical models presented for maize in United States and Africa. The two main mechanisms responsible for yield loss in the model were faster crop development and moisture stress, although only the latter showed a nonlinear response to higher temperatures. By performing simulations for increased temperatures with and without moisture stress turned on in the model, it was possible to identify the relative role of moisture in the temperature-yield relationship (Figure 5). In some cases, such as Iowa, simulations showed a negligible effect of moisture stress while in several African sites moisture stress explained a substantial fraction of the yield decline, with this fraction increasing for higher temperatures. Photosynthesis rates were also reduced at high temperatures and temperature limits to photosynthesis became a more important limit to crop yields as warming occurred. Unfortunately, the crop models do not adequately represent the temperature dependency of several key processes, such as respiration, pollen formation, or grain filling, and therefore provide only limited insight into the overall response of crops to high temperatures.

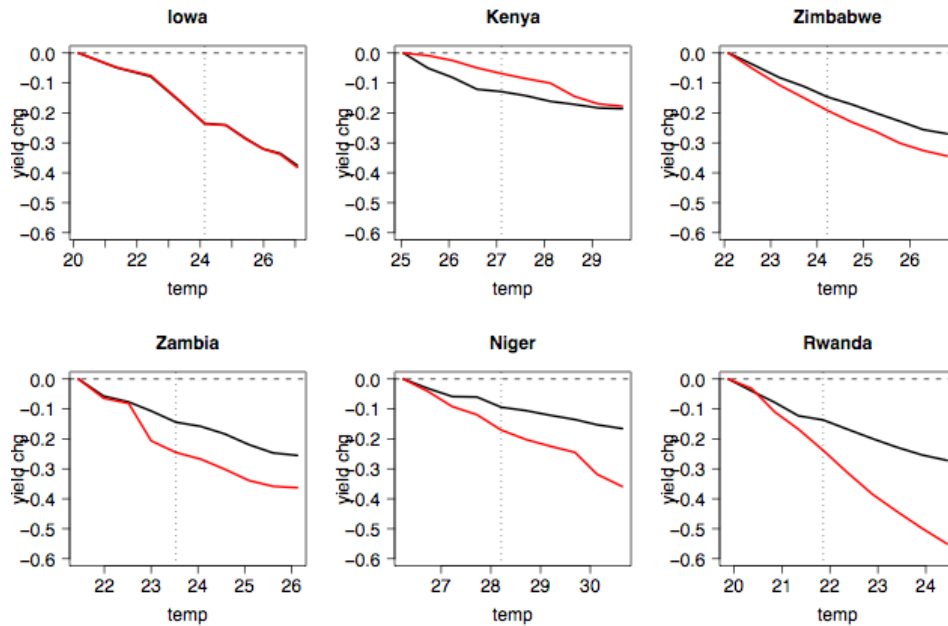


Figure 5. Simulated yield losses (in red) for different levels of warming at selected sites. Yields were simulated with CERES-Maize. X-axis indicates average growing season temperature. Black lines indicate yields when water stress was artificially removed.

Genetic resources for drought and heat tolerance

Successful development of crops with any particular trait depends on the ability of crop scientists to access sufficient genetic variability for this trait. Without this variability, even the best efforts will be hampered by a limited range of genetic possibilities. Access to this variability, in turn, requires that the relevant varieties or wild relatives be (1) collected, (2) properly characterized, and (3) made available to scientists that desire access. Material presented at the meeting indicated that all three of these requirements are far from being met in most instances.

Collection of genetic variability for the major cereals has been fairly complete in some respects. Roughly 90% of genetic variability for the three main cereals is believed to be contained in seed banks around the world. However, many other crops are much more poorly collected, particularly non-cereal crops that are often more expensive to preserve ex situ. Even in cases where genetic diversity is in theory preserved in seed banks, the traits of these seeds are poorly known. Basic characteristics such as disease resistance or relative drought tolerance, for instance, are frequently unknown. This lack of investment in characterization, both in terms of phenotypes and genotypes, makes it very difficult for breeders to make effective use of genetic diversity contained in current collections. In addition to deficiencies in information, there are inadequacies in information systems. Progress is being made, however, in developing a system that would allow breeders to search for needed traits across collections.

Added to these impediments are substantial institutional factors. First, there is a lack of investment in characterization and pre-breeding activities which are critical to incorporating the extremes of available diversity into lines that can be readily crossed with currently grown varieties. The demand from breeding institutions for bank seeds is therefore weaker than it would be if characterization and pre-breeding were dedicated activities. Second, seed bank managers may have resources to conserve but are often reluctant to share their holdings due to political sensitivities. Seed banks' loyalties may also lie with their specific institution or country and not with a particular species or trait. The net result of these and other factors is that more than half of the seedbanks around the world probably do not send a single sample outside the country or institution within a typical year. In practical terms, access to genetic resources globally is obtained from a relatively small number of international centers and a few prominent countries, most of them developed.

Breeding for drought and heat tolerance in major cereals

Several presentations, from both public and private sector participants, reviewed recent efforts at developing crops with improved drought and heat tolerance. Some themes were common to all presentations. First, it was noted that varieties with improved performance under abiotic stress may exhibit sub-optimal yields when grown in stress-free environments. As one participant stated, "If you select for cactus-like tolerance, you will get cactus-like productivity." This tradeoff is not universal to all traits, and the goal of most current activities is to identify varieties that out-perform both with and without stress (Variety 4 in schematic of Figure 6).

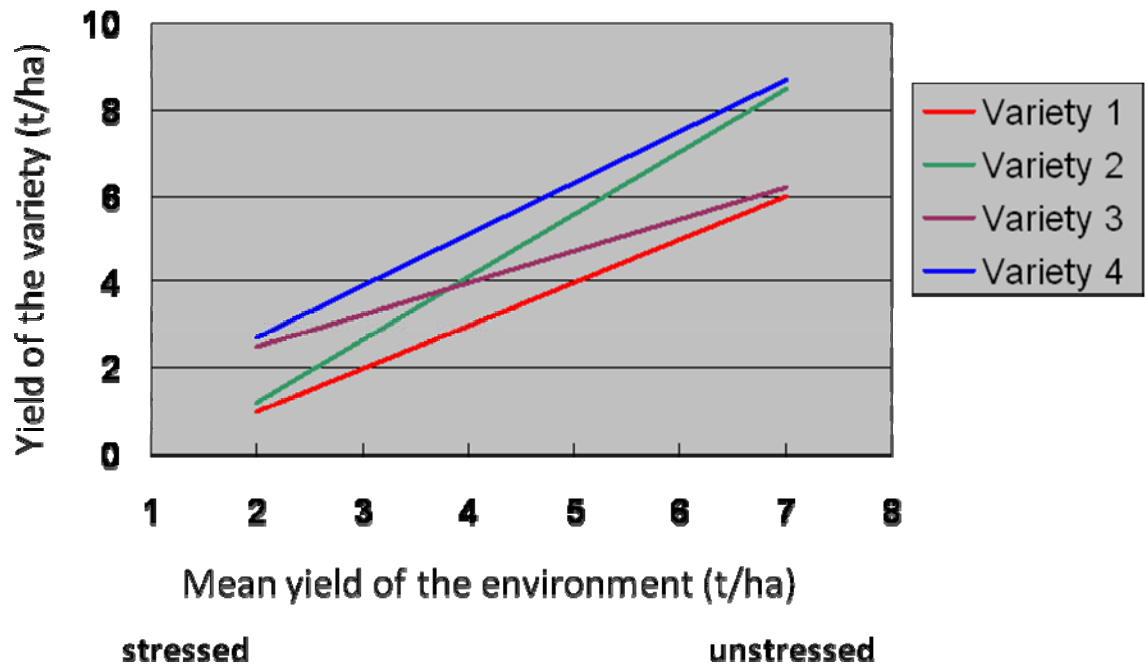


Figure 6. Schematic of different hypothetical crop varieties. Varieties that perform well under stress often exhibit yield penalties in unstressed environments (Variety 3 vs. Variety 2). However, a few varieties are able to perform well in both extremes (Variety 4 vs. Variety 2).

Yield tradeoffs are an impediment to the release of stress tolerant lines, for both economic and institutional reasons. Economically, farmers often make most of their money in high-yielding years, and are unwilling to sacrifice performance in these years to slightly improve yields in harsh years. Institutionally, most varieties are developed, tested, released and demonstrated in optimally managed trials. This is also the case in most stressful or resource constrained countries and regions where only a very small proportion of the farmers achieve those kinds of yield levels. Results from trials conducted under stress conditions are often discarded because results are more variable. It was suggested that in regions with frequent stress, paired demonstration plots – where varieties are grown both under recommended management practices and under farmer representative input conditions – would help to clarify the tradeoffs for farmers and possibly promote the adoption of more stress-tolerant varieties. Also variety release authorities need to be conscious that variety releases based on trials grown under yield potential conditions are inappropriate if the majority of farmers grow their crops under more stressful conditions.

All presenters also emphasized that drought has received far more attention than heat stress for all crops and both public and private sectors. There are good reasons for this, namely that drought is perceived as a more important constraint on yields in current climate. In the United States, for example, roughly 2/3 of major crop losses were attributed to drought in the early 1990s. Progress on drought in recent years has been promising in many instances, particularly for maize. An important innovation in

breeding has been the use of managed stress trials, where varieties are grown under irrigation in reliably dry locations, and then irrigation is turned off at specified times. This allows breeders to precisely control stress levels and thereby better screen for drought tolerance.

Managed drought trials conducted by CIMMYT in Africa since 1996 have produced hybrids with 15-20% yield gains over hybrids developed by breeding programs that do not use managed drought stress. These trials are ongoing and continue to produce varieties with improved performance under drought stress, while maintaining high yields under optimum conditions. Private seed companies have adopted the managed stress trial approach in breeding programs mostly oriented towards the United States, and report significant progress based on this approach. Both Pioneer and Monsanto, for instance, use managed drought to identify inbreds and hybrid varieties with specific drought tolerant genes, and the first of these are at or near the commercialization stage.

In wheat and rice, breeding efforts have historically been focused more on raising yield potential in irrigated environments, although this has shifted recently with the implementation of managed drought screening approaches at CIMMYT and IRRI. This contrasts with maize which is largely grown under rainfed conditions and therefore breeders have more frequently contended with water stress. In fact, much of the progress in maize yield in temperate environments is believed to result from increased stress tolerance, related to higher planting densities since many modern varieties do not outperform old varieties at low planting densities.

In contrast to drought, progress on heat tolerance has been very limited. Some work on rice has identified varieties that flower earlier in the day, and therefore escape the peak temperatures that can reduce pollen shedding, which leads to spikelet sterility. However, these traits have not been actively incorporated into commonly grown varieties. One positive trend in new varieties is that the canopy architecture results in panicles that are surrounded by leaves and often up to 2 °C cooler than ambient temperatures. Panicles in traditional varieties are typically exposed to sunlight and higher temperatures, and therefore traditional varieties are believed to be more sensitive to warming than modern varieties.

In wheat, some early maturing varieties have shown improved performance under hot conditions in India, presumably because they escape the worst of the heat and moisture stress. Wild relatives of wheat also show promise in thriving under high temperatures, but work to incorporate these traits into existing varieties has not been a focus of recent efforts. The ability to access soil water and maintain cool canopy temperatures appear key traits for tolerance of both drought and heat stress in hot and dry environments, although in hot and humid systems transpiration becomes a less effective means of avoiding heat stress.

Less work on maize has focused on heat as compared to rice and wheat, because as a C₄ crop maize can thrive under higher temperatures. It is also widely perceived that breeding for drought is likely to bring along traits that do well under high temperatures. The importance of heat stress may have been underestimated for maize given that results presented at this conference show maize yields decreasing with the number of days exceeding 30 C. However, it was noted that transgenic research

focused on heat stress in maize has gained momentum very recently, although it is too soon to know the outcomes or even the strategies behind these efforts.

Finally, all participants agreed that improvement of crop varieties, through a combination of breeding and biotechnology, will have maximal benefits if combined with improved agronomy. Agronomic advances include conservation agriculture, which involves reduced tillage and permanent soil cover, and rainwater harvesting. There are likely important interactions between agronomy and genotypes, and therefore testing varieties under a range of management systems could improve the eventual performance of the cropping system in drought conditions.

Selected summary points from the discussion are highlighted in Box 1. In addition, several topics were mentioned as in need of further analysis and discussion, possibly in future meetings. These are outlined briefly below:

1) A major concern in wheat, and in other crops, is whether biotic stresses will become more severe or widespread in a new climate, and specifically whether abiotic stresses will interact with these biotic stresses. For example, hot conditions could favor certain diseases, weeds or pests, and drought or heat stressed crops could be more susceptible to disease. Yet progress on this topic has been slow, in part because of the complex nature of pest and disease responses, but also likely in part because of a lack of effective communication across disciplines. The climate community, for instance, understands very little about which specific variables are needed to predict pest and disease response.

2) There is surprisingly little information available from field-based studies that look at genetic variation under future climates. Most trials examining the impact of heat and increased CO₂ levels examine distinct stages in the greenhouse and rarely look at performance over an entire season or larger numbers of varieties. Potential contributions from native genetic variation to securing crop production in future climates are hence little known, understood and not used.

3) Efforts on abiotic stresses in cereals may hold important lessons for improvements to less major crops (e.g., the next ten most important sources of calories.) Although some of these, such as cassava, are typically quite heat and drought tolerant, others would likely benefit greatly from breeding efforts to improve performance under heat and moisture stress. Bringing together scientists working on major and minor crops could help to bring work on the latter up to speed more quickly, especially considering that there are much fewer breeders working on the minor crops.

4) Although improved yields are likely to benefit farmers, the overall goal of adaptation should be to ensure that livelihoods, not necessarily just yields, are improved. This distinction may be important especially as markets develop for aspects of agricultural systems other than yields. For example, bio-energy markets are rapidly developing in many areas and may provide opportunities to generate income from crop residues, or dedicated biomass crops. Simultaneously, efforts to mitigate greenhouse gases have spawned markets for carbon credits, whereby farmers could receive money for preserving soil carbon or reducing methane and nitrous oxide emissions. Whether these change the adaptation

strategies from those that focus only on yields remains to be seen, but is a topic worthy of more focused attention.

Box 1. A Dozen Summary Points, from Materials Presented and Discussed at Meeting

1. All crops in all regions are nearly certain to see higher temperatures in the next few decades, consistently breaking records both for average growing season temperatures and number of days above critical thresholds, such as 35 °C (see Figure 1). Moisture levels will increase in a few regions but decrease in several important growing areas, including much of North America, Europe, Africa, Central America, and Australia.
2. There is some scope for moving crops into new areas, but poor soils, lack of infrastructure, and other biophysical and socio-economic factors make this challenging. Adapting crops in their current locations is therefore a major need.
3. There is strong evidence from studies in the U.S. that yields of maize (and several other crops) exhibit a nonlinear reduction when exposed to temperatures exceeding 30 °C (see Figure 3). All participants agreed that understanding of the physiological response of crops to high temperatures is surprisingly limited. Faster crop development and soil drying with higher temperatures are likely the two key processes determining overall temperature response in current climate. Other effects of high temperatures, including on photosynthesis, respiration, and heat damage of reproductive organs are less understood.
4. Incremental adaptation of crops to climate change is inevitable, because of the continual field testing of varieties. But all participants agreed that reliance on this alone would likely not be enough for successful adaptation to future temperatures, and that much more could be achieved with concerted efforts to identify and employ genetic traits related to heat and drought stress.
5. Relatively little work is being done to develop heat tolerant crops relative to drought, especially in maize. There have been recent efforts in rice and wheat, with some promising results, such as toward earlier pollen shedding in rice. However, both private and public sector participants agreed that little emphasis has been placed on heat stress to date, although some investments in the private sector have recently been made.
6. Major improvements for heat and drought tolerance are almost certainly based on the simultaneous improvement or modification of several traits and genes, which is more difficult to achieve than for single gene traits.
7. Managed drought trials have been instrumental in development of drought tolerant varieties, in both public and private sectors. Varieties from managed drought trials consistently outperform those screened only for yield potential and then tested in multi-environment trials. At CIMMYT, average yield gains of 15-20% have been achieved under random stress conditions and at farmer representative yield levels in Africa after 6 years and 3.5M investment, and much more in trials that were only exposed to drought but not other stress factors.

8. Some traits that confer better performance under heat or moisture stress have associated yield penalties under favorable conditions relative to existing varieties. However, this yield tradeoff does not occur with all traits, and both breeding and biotechnology approaches have successfully produced drought tolerant varieties that exhibit no penalty in favorable environments. In general, breeding for multiple traits results in fewer varieties for a given investment level.

9. In both developed and developing countries, there is currently little willingness to sacrifice yield potential for greater tolerance to stress. There are sound economic reasons for this in some but not all cases. For example, in Africa most crops are grown in stressed environments, but varieties are released based on trials performed in optimal conditions. Development, testing, release and demonstration of new varieties under both optimal and stressed conditions would likely accelerate the use of stress-tolerant varieties.

10. The genetic resource base for developing new climate-ready crop varieties has not been adequately explored or shared, with many seed banks distributing few if any varieties to other institutions and countries. There is a great need to complete the collection and secure the conservation and availability of the complete genepools of major crops and to better connect the seed bank and crop development communities by aggressively investing in better characterizing phenotypes and genotypes of existing collections, including their wild relatives, and by creating searchable electronic databases which are globally accessible. Given the magnitude of impact of climate change on crop production and livelihoods, it is surprising that no investment is directed at understanding the nature and the value of the native genetic variation locked away in seed banks, and in making valuable genetic variation useful to breeders worldwide.

11. Improved agronomy is an essential complement to breeding and biotechnology. Particularly for managing moisture stress in rainfed systems, agronomy may well offer even greater potential benefits than improved crop varieties, provided bottlenecks for input and output markets are overcome and farmers are better supported to experiment with best bet options.

12. There are several important differences between developing and developed countries, and between high potential and more stress prone environments. Developing countries and stress prone areas tend to have much less private sector investment in breeding, seed sector development and variety adoption is slower, there is more reliance on open-pollinated maize varieties, and other stress factors (nutrient deficiency, acidity, salinity, low soil organic matter) may compound the impacts of drought and heat. Also, the pace of warming is considerably faster in tropical nations relative to historical experience than in temperate countries.

Recommended Priorities

The group assembled at this meeting came in with a wide range of experience and perspectives. There was surprise expressed by several crop scientists on how dire the climate projections appear, and also on how uncertain many aspects of climate change are. Conversely, several climate scientists were surprised by the poor state of seed bank collection and utilization, and the lack of understanding in how crops respond to high temperatures. On a more optimistic note, the rapid progress achieved in managed stress trials, the ability to consistently produce new stress-tolerant varieties without yield penalties at

yield potential, and the significant benefits that appear from single-gene transfers in the private sector surprised many participants. Even with the disparate backgrounds, all participants agreed on several needs by the end of the meeting. These are outlined below, beginning with two near-term recommendations and ending with two longer-term objectives.

First, it was clear that more communication between the climate and crop communities would be beneficial. In particular, the crop community has been trained to target varieties to existing climate, and do not often appreciate how quickly these environments could be changing. Similarly, the climate community often assumes that crop responses to weather will remain similar in the future as in the past, without understanding the differences in the most recent varieties. We therefore recommend **1) greater interactions between climate and crop scientists, possibly through regular symposia to provide updates on recent developments in each field.**

Second, there appears to be significant opportunity to improve understanding of crop responses to abiotic stresses, and in particular high temperatures, by combining existing geospatial datasets on crop performance and weather. We therefore recommend **2) analysis of historical and future trial data with co-located or nearby weather data to quantify heat and moisture effects on yields.** CIMMYT, for instance, has conducted thousands of trials across multiple sites and years, and this data has not yet been adequately mined for insight into climate responses. Similarly, there may be opportunity to learn from private sector trials, for which reliable weather data is more likely available. For future trials, a near-term and relatively inexpensive need is to ensure that reliable weather measurements are taken at trial sites.

The above recommendations entail relatively short-term and low-cost investments, but the group also identified two major long-term needs. First, we suggest that **3) efforts to develop heat tolerant varieties of major cereals needs to be greatly accelerated, with dedicated trial stations established in appropriate locations.** The group did not identify particular stations, but envisioned that analysis of temperature, rainfall, and radiation datasets, along with climate projections, should allow the identification of sites that serve as analogs to future conditions in major growing regions.

Finally, there is a major need to better characterize and utilize crop genetic resources in order to realize successful adaptation of crops to climate change. We recommend **4) greater investment is made in phenotyping and genotyping the native genetic variation contained in seed banks, developing a digital database of these characteristics to facilitate their use by the crop development community, and collecting the remaining diversity (particularly that associated with traits of value to crop adaptation to climate change).** Users of seed bank facilities, such as breeders, should play a key role in shaping these efforts to ensure that the end result is useful, and investment should be directed at those seed banks that implement a policy of making their gene pools available beyond institutional and country limits.